



The Resonantly Diode Pumped, Cryogenic $\text{Ho}^{3+}:\text{YVO}_4$ 2.05- μm Laser

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14. ABSTRACT We report what is believed to be the first laser operation based on Ho^{3+} -doped yttrium orthovanadate (YVO_4). The cryogenic (77 K) $\text{Ho}^{3+}:\text{YVO}_4$ was resonantly diode-pumped at $\sim 1.93 \mu\text{m}$ to produce up to 1.6 W of continuous wave (CW) output power at $\sim 2.054 \mu\text{m}$. The laser had a slope efficiency of $\sim 38\%$ with respect to absorbed power. We have measured the absorption and stimulated emission cross sections of the $\text{Ho}^{3+}:\text{YVO}_4$ at 77 K, 175 K, and 300 K and present the calculated gain cross section spectrum at 77 K for different excited state inversion levels.					
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1. The Diode-pumped Holmium-doped Solid-state Laser

Holmium (Ho) as a rare earth laser ion continues to gain the interest of the laser community as it emits at eye-safe wavelengths around 2 μm and is useful for atmospheric sensing and medical applications. Diode-pumped holmium co-doped thulium (Tm): yttrium lithium fluoride (YLF) (1) or yttrium aluminium garnet (YAG) (2) host lasers have been demonstrated and while the two-for-one process used in pumping Tm at around 800 μm is attractive due to the availability of efficient 800- μm laser diode pump sources, emission at 2.1 μm guarantees a large heat loading of the laser crystal due to the high quantum defect. Conversely, resonant pumping of singly doped YAG (3), lutetium aluminum garnet (LuAG) (4) and most recently, yttrium oxide (Y_2O_3) (5) hosts allows for low quantum defect-low thermal loading of the laser crystal. We present, for what we believe is the first time, lasing action of a resonantly pumped $\text{Ho}^{3+}:\text{YVO}_4$ crystal as well as the absorption, emission and gain cross sections of Ho: yttrium orthovanadate (YVO_4) at 77, 175, and 300 K.

2. Determination of $\text{Ho}^{3+}:\text{YVO}_4$ Absorption and Emission Spectroscopy

The laser host, $\text{Ho}^{3+}:\text{YVO}_4$, is a bi-refrigent material and as such exhibits two sets of absorption and emission spectroscopy. Using an Fourier transform infrared (FTIR) polarization sensitive spectrometer, we measured the absorption of $\text{Ho}^{3+}(1\%):\text{YVO}_4$ in the wavelength range of 1800 to 2200 nm with a resolution of 1 cm^{-1} . Care was taken to limit the absorption of our sample to an absorbance of 2 as the FTIR becomes unreliable in its intensity measurement thereafter. Three sets of absorption spectra taken at 77, 175, and 300 K, marked as π and σ polarization corresponding to polarization parallel and perpendicular to the YVO_4 c-axis are shown in figure 1. At the temperature 77 K, the peak absorption cross sections, in the 1900 to 1970 nm range are approximately $7 \cdot 10^{-20} \text{ cm}^2$ (compare to $\text{Ho}^{3+}:\text{YAG}$ at $5 \cdot 10^{-20} \text{ cm}^2$, 1900–1915 nm, our measurements). These values decrease to $\sim 2.5 \cdot 10^{-20}$ and $\sim 1 \cdot 10^{-20} \text{ cm}^2$ at 175 and 300 K, respectively.

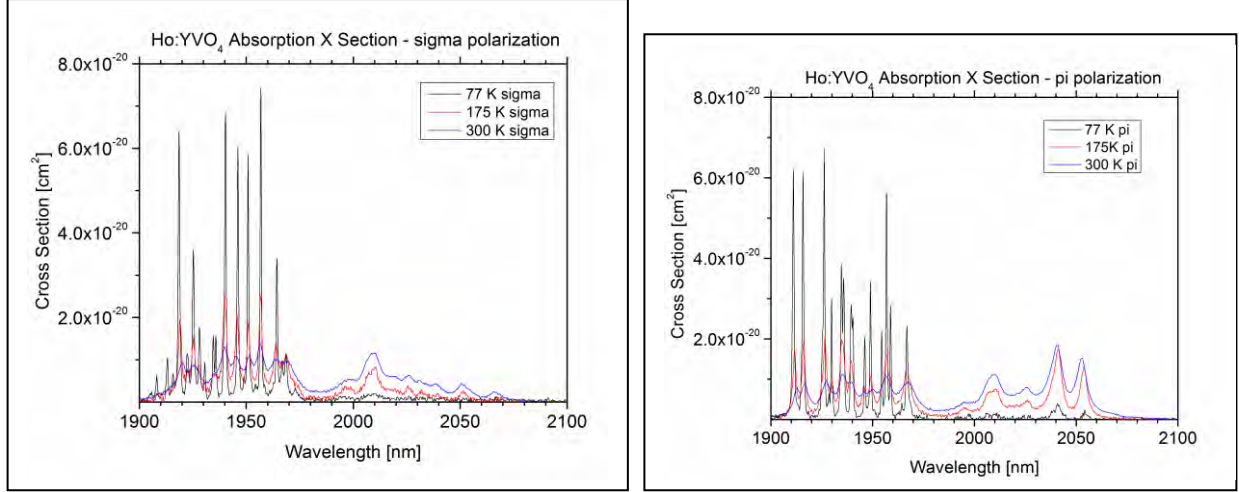


Figure 1. $^5I_8 - ^5I_7$ absorption cross section of $\text{Ho}^{3+}:\text{YVO}_4$ at 77, 175, and 300 K. Comparison between $E//\sigma$ and $E//\pi$.

Using the method of reciprocity, we calculated the stimulated emission cross section of $\text{Ho}^{3+}:\text{YVO}_4$. As can be seen in figure 2, two strong emission peaks for π polarization are visible at 2041 and 2054 nm. Recent work in Tm, $\text{Ho}^{3+}:\text{YVO}_4$ (6) confirms the possibility of lasing at these two wavelengths. However, our calculation of the gain cross section from 0–25% inversion levels at 77 K (see figure 3) predict that lasing action is most likely to occur first at the 2054 nm wavelength. This was confirmed by experiment. Unfortunately, due to re-absorption at room temperature, lasing is only possible with large inversion of over 60%. Such high inversion values require high brightness fiber laser source, such as the Tm fiber laser.

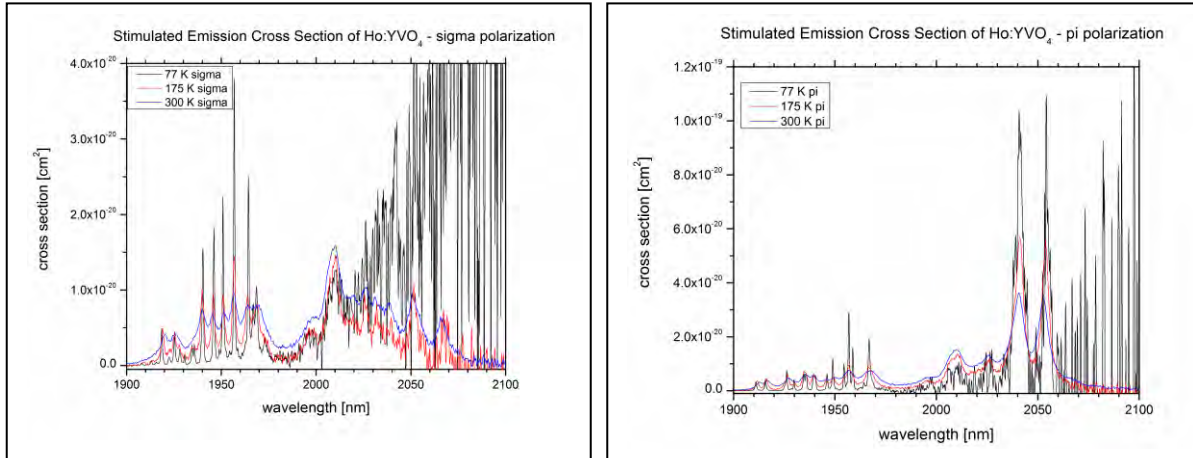


Figure 2. $^5I_7 - ^5I_8$ stimulated emission cross section of $\text{Ho}^{3+}:\text{YVO}_4$ at 77 K. Comparison between $E//\sigma$ and $E//\pi$.

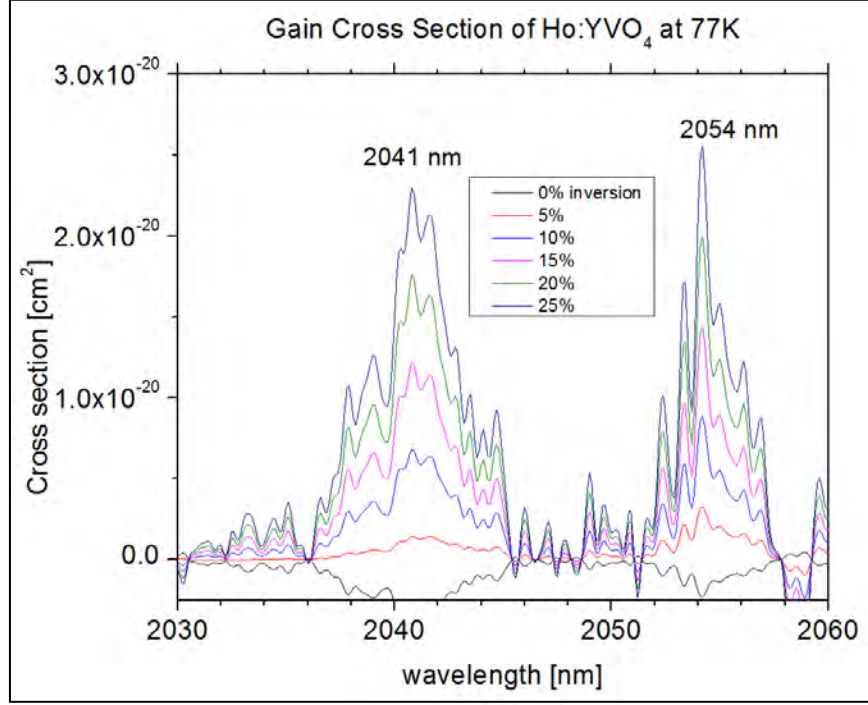


Figure 3. $^5I_7 - ^5I_8$ gain cross section of $\text{Ho}^{3+}:\text{YVO}_4$ at 77 K for $E//\pi$ as calculated for 0–25% inversion.

3. Experimental Setup and Lasing Results

Our laser testbed setup consisted of a $\text{Ho}^{+3}(0.5\%):\text{YVO}_4$ single crystal slab measuring $3 \times 8 \times 13 \text{ mm}^3$ sandwiched between two oxygen-free copper (OFC) blocks and held at 80 K. The laser cavity was 250 mm in length and used a 85% reflectivity outcoupler. The crystal was a-cut such that the c-axis was normal to the broad surface of the crystal (figure 4). The narrow end faces were AR coated for at 1900–1950 nm for σ -polarization and AR coated for 2000–2175 nm for π -polarization. Published data on the thermal conductivity of neodymium ($\text{Nd}(0.5\%):\text{YVO}_4$) indicates that the c-axis is 50% more conductive than the a-axis (7), that is 60 [W/m-K] vs 40 [W/m-K] at 77 K.

The crystal as shown in figure 4a was pumped by a 400 μm , 0.22 NA fiber coupled diode laser source emitting in a range from 1900 nm to 1930 nm depending on the diode drive current. The beam was focused to a measured 1.1 μm diameter spot within the crystal. The cavity mode diameter was calculated to be 0.75 μm . The laser performed with 38% optical-to-optical (absorbed) efficiency with a continuous wave (CW) power of 1.6 as shown in figure 4b and emitted at 2054 nm (see inset). The modest laser efficiency is due in large part to the poor overlap of pump to laser cavity modes. Optical-to-optical laser efficiency can be expected to rise >70% once pump and laser cavity mode overlap is optimized.

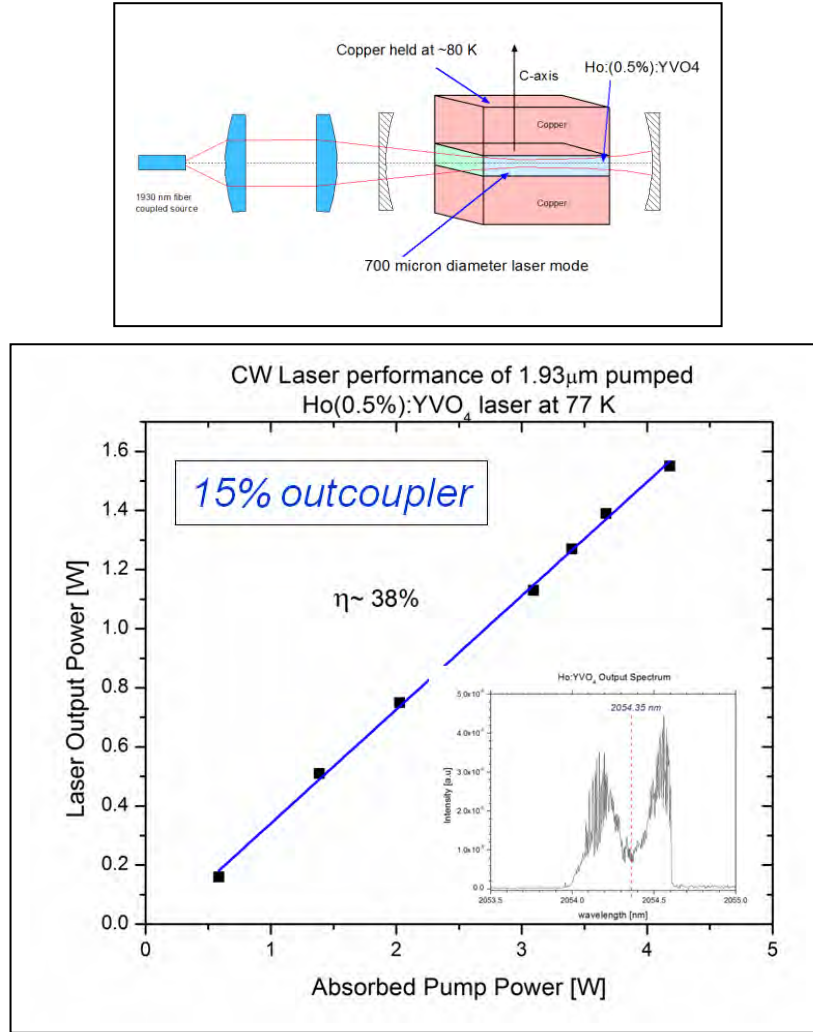


Figure 4. (a) Laser setup of diode pumped (1.93 μm) cryogenically cooled Ho³⁺:(0.5%):YVO₄ and (b) performance of cryogenically cooled Ho³⁺:(0.5%):YVO₄ laser with laser spectral output in inset.

4. Conclusion

We have demonstrated, for what we believe is the first time, a resonantly pumped Ho³⁺:YVO₄ laser at 77 K emitting at 2054 nm. The laser performed with 38% optical-to-optical (absorbed) efficiency and with a CW power of 1.6 W. We have also presented the absorption and emission cross sections of Ho³⁺:YVO₄ at 77, 175, and 300 K.

5. References

1. Cornacchia, F.; Di Lieto, A.; Maroni, P. et al. A cw Room-temperature Ho,Tm: YLF Laser Pumped at 1.682 μm . *Applied Physics B-Lasers and Optics* **2001**, 73 (3) 191.
2. Bundi, P. A.; Pomeranz, L. A.; Lemons, M. L.; Schunemann, P. G.; Pollak, T. M.; Chicklis, E. P. 10W Mid-IR Holmium Pumped ZnGeP₂ OPO, OSA TOPS, Vol. I9, *Advanced Solid State Lasers* 1998.
3. Esterowitz, Allen L.; Goldberg, L.; Weller, J. F.; Storm M. Diode-pumped 2 μm Holmium Laser. *Electron. Lett.* **1986**, 22 (18), 947.
4. Barnes, N. P.; Amzajerjian, F.; Reichle, D. J. et al. 1.88 μm InGaAsP Pumped, Room Temperature Ho:LuAG Laser. *2009 Conference on Lasers and Electro-Optics (CLEO), CWH4*, (2009).
5. Newburgh, G. A.; Word-Daniels, A.; Michael, A.; Merkle, L. D.; Ikesue, A.; Dubinskii, M. Resonantly diode-pumped Ho³⁺Y₂O₃ ceramic 2.1 μm laser. *Opt Exp.* **2011**, 19, 4, 3604.
6. Yao, B. Q.; Li, G.; Meng, P. B.; Zhu, G. L.; Ju, Y. L.; Wang, Y. Z. High Power Diode-pumped Continuous Wave and Q-switch Operation of Tm,Ho:YVO₄ Laser. *Laser Phys. Lett.* **2010**, 7, 857.
7. Zelmon, David E. et al. Revisiting the Optical Properties of Nd Doped Yttrium Orthovanadate. *App. Opt.* **2010**, 49 (4), 644.

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